HE 0437−5439 – an unbound hyper-velocity main-sequence B-type star*

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ABSTRACT

We report the discovery of a 16$^{\rm th}$ magnitude star, HE 0437−5439, with a heliocentric radial velocity of $+723 \pm 3$ km s^{-1}. A quantitative spectral analysis of high-resolution optical spectra obtained with the VLT and the UVES

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*Based on observations collected at the European Southern Observatory, La Silla and Paranal, Chile (Proposal No. 68.D-0192 and 70.D-0334).

spectrograph shows that HE 0437−5439 is a main sequence B-type star with $T_{\rm eff}$=20 350 K, $\log(g)$ = 3.77, solar within a factor of a few helium abundance and metal content, rotating at $v\sin(i)$ = 54 km s^{-1}. Using appropriate evolutionary tracks we derive a mass of 8 $M_\odot$ and a corresponding distance of 61 kpc. Its galactic rest frame velocity is at least 563 km s^{-1}, almost twice the local Galactic escape velocity, indicating that the star is unbound to the Galaxy. Numerical kinematical experiments are carried out to constrain its place of birth. It has been suggested that such hyper-velocity stars can be formed by the tidal disruption of a binary through interaction with the super-massive black hole at the Galactic center (GC). HE 0437−5439 needs about 100 Myrs to travel from the GC to its present position, much longer than its main sequence lifetime of 25 Myrs. This can only be reconciled if HE 0437−5439 is a blue straggler star. In this case, the predicted proper motion is so small that it can only be measured by future space missions. Since the star is much closer to the Large Magellanic Cloud (LMC, 18 kpc) than to the GC, it can reach its position from the center of the LMC. The proper motion predicted in this case is about 2 mas yr^{-1}(relative to the LMC), large enough to be measurable with conventional techniques from the ground. The LMC origin could also be tested by a high-precision abundance analysis.

Subject headings: stars: individual (HE 0437−5439) – stars: distances – stars: early-type – Galaxy: center – Galaxy: halo

1. Introduction

Main sequence B-type stars located far away from the galactic plane are a rare, albeit known phenomenon. They are believed to be run-away stars ejected from the galactic plane shortly after their formation (see e.g. Tobin 1987; Ramspeck, Heber & Edelmann 2001). Up to recently none of the known run-away B-type stars were found to have a velocity exceeding the Galactic escape velocity.

Brown et al. (2005) discovered a faint late B-type star, SDSS J090745.0+024507, with a heliocentric radial velocity of 853 ± 12 km s^{-1} (galactic rest-frame velocity of 709 km s^{-1}). This so-called hyper-velocity star (HVS) is unbound to the galaxy and Brown et al. (2005) conclude that it was ejected from the Galactic center (GC) because its radial velocity vector points 173.8° from the latter. Photometric investigations showed it to be a slowly pulsating B-type main sequence star (Fuentes et al. 2005).

Hills et al. (1988) predicted that velocities as high as 4 000 km s^{-1} can be gained by the disruption of a binary through interaction with the massive black hole in the galactic center (Schödel et al. 2002). Yu & Tremaine (2003) considered two additional processes that eject hyper-velocity stars in addition to the tidal breakup of binary stars by the central black hole, i.e. close encounters of two single stars and three-body interactions between a star and a binary black hole. While the ejection rate by close encounters of two single stars is found to be negligible, as much as $\sim 10^{-5}$ HVS/yr could be ejected by the tidal breakup scenario and even $\sim 10^{-4}$ HVS/yr if the Galactic center hosts a binary black hole.

We report the discovery of a second hyper-velocity star, HE 0437−5439 ($\alpha_{2000} = 4^{\rm h}38^{\rm m}12\overset{\rm s}{.}8$, $\delta_{2000} = -54°33'12''$), much brighter ($16\overset{\rm m}{.}2$) than the HVS SDSS J090745.0+024507. The star was found during a spectroscopic follow-up campaign of subluminous B (sdB) star candidates from the Hamburg/ESO survey (see e.g. Christlieb et al. 2001).

Low resolution spectra were obtained on 2001 November 20$^{\rm th}$ at ESO, La Silla, with the Danish 1.5 m telescope and the DFOSC spectrograph. The spectrum of HE 0437−5439 is very similar to a normal main sequence B-type star. Most remarkable is its very large radial velocity of $v_{\rm rad} = +700 \pm 50$ km s^{-1}. To improve this measurement and check for radial velocity variations we observed the star twice again on 2002 November 14$^{\rm th}$ (05:00 UT and 08:37 UT) at the ESO Paranal observatory using the VLT UT2 8 m telescope (Kueyen) equipped with the UVES high-resolution echelle spectrograph covering the spectral range from 3300 to 6600Å at a resolution of 0.2Å and a S/N of 5. Radial velocities were measured with the FITSB2 program (Napiwotzki et al. 2004). The spectra yield the same very high radial velocity of 723 ± 3 km s^{-1} (721 and 726 km s^{-1}, respectively), consistent with that from the low-resolution spectrum. To our knowledge it is the second largest radial velocity ever measured for a faint blue star at high galactic latitudes. Therefore HE 0437−5439 qualifies as a hyper-velocity star.

Since the star lies at high galactic latitude ($l_{II} = 263.04°$, $b_{II} = -40.88°$) one has to consider the possibility that it may not be a hot massive star but a low mass evolved star that somehow mimics a main-sequence B-type star (Tobin 1987). Fortunately, the high resolution spectra allow us to carry out a detailed quantitative spectroscopic analysis, i.e. to derive temperature and gravity, elemental abundances, and the projected rotational velocity of HE 0437−5439 (Section 2) in order to prove or disprove its nature as a young massive star. Its mass and distance is then derived from evolutionary tracks (Section 3) and the time of flight from the plane is estimated from galactic orbit calculations and compared to its evolutionary life time to search for the likely place of birth (Section 4).

2. Spectral analysis

The stellar atmospheric parameters (effective temperature $T_{\rm eff}$, surface gravity $\log(g)$, and photospheric helium abundance $n_{\rm He}/n_{\rm H}$) were determined by matching synthetic line profiles calculated from model atmospheres to all Balmer (mainly H_β up to H_{15}) and He I line profiles present in the observed spectra. A grid of metal-line blanketed LTE model atmospheres (Heber, Reid & Werner 2000) was used. The models are plane parallel and chemically homogeneous and consist of hydrogen, helium, and metals (solar abundances). The matching procedure uses a χ^2 fit technique described by Napiwotzki et al. (1999) to determine all three atmospheric parameters simultaneously. Beforehand all spectra were normalized and the model spectra were folded with the instrumental profile (Gaussians with appropriate width). The fit result is shown in Fig. 1.

From the co-added high-resolution spectra we determined the atmospheric parameters to be $T_{\rm eff} = 20\,354 \pm 116$ K, $\log(g) = 3.77 \pm 0.02$ (cgs), and $\log(n_{\rm He}/n_{\rm H}) = -0.94 \pm 0.02$. The errors are statistical ones. The error budget, however, is dominated by systematic errors. From our previous experiences with the analysis of similar UVES spectra (Lisker et al. 2005) we adopt $\Delta T_{\rm eff} = 360$ K, and $\Delta \log(g) = 0.05$ (cgs). Taken at face value the helium abundance would be slightly above solar. In order to verify it, we fitted the spectrum again but keeping the He abundance at the solar value. The quality of the fit is as good as for the simultaneous fit of all three parameters. Therefore, we conclude that the star's helium abundance is solar to within 0.06 dex. Spectra of much better S/N would be needed to narrow down the error range.

The rotational velocity is determined by a χ^2 fit to the same lines, for which the atmospheric parameters are kept fixed. Synthetic spectra were folded with rotational profiles (limb darkening coefficient 0.4) for various values of $v\sin(i)$. $v\sin(i) = 54 \pm 4$ km s^{-1} (3σ error) results.

Because the exposure times were short (10 min.) the spectra are quite noisy. Nevertheless metal lines (C II, N II, O II, Mg II, Si II, and S II) can marginally be measured in the UVES spectra. However, due to the rotational line broadening a quantitative abundance analysis is rendered difficult. A rough abundance estimate, however, can be obtained by comparing synthetic spectra to the observation for solar metallicity as well as for twice and half solar values. The microturbulent velocity was assumed to be zero. A solar metallicity spectrum appears to be consistent with the data (see Fig. 2).

In summary, the results of the quantitative spectral analysis strongly suggest that HE 0437−5439 is a young massive star since its effective temperature and gravity is typical for main sequence B-type stars. The normal metallicity supports this interpretation.

While some low mass evolved stars (HB or post-HB stars) mimic massive B-type stars to some extent the high rotational velocity and normal helium abundance of HE 0437−5439 rules out an evolved star, because B-type horizontal branch stars are known to be very slow rotators ($< 8 \mathrm{km\,s^{-1}}$) as well as helium deficient (Behr 2003). Hence, there is no doubt that HE 0437−5439 is a main sequence B-type star.

3. Mass, evolutionary timescale and distance

Having shown HE 0437−5439 to be a main sequence B-type star, we can estimate its mass by comparing its position in the ($T_{\rm eff}$, $\log(g)$) diagram to evolutionary tracks (see Fig. 3). From solar metallicity models (Schaller et al. 1992) we derive $8.4 \pm 0.5 M_\odot$, while a slightly lower mass of $8.0 \pm 0.5 M_\odot$ results from models with $Z = 0.008$ (Schaerer et al. 1993). The evolutionary time can be interpolated to be about 25 Myr for solar composition and about 35 Myr for the lower metallicity (appropriate for the LMC, see Sect. 4).

Using the mass, effective temperature, gravity and apparent magnitude ($V = 16\overset{\rm m}{.}2 \pm 0\overset{\rm m}{.}2$), we derive the distance as described by Ramspeck, Heber & Edelmann (2001) to $d = 61 \pm 12$ kpc.

Correcting for the solar reflex motion and to the local standard of rest, the Galactic velocity components can be derived from the radial velocity ($U = -55$ $\mathrm{km\,s^{-1}}$, $V = -317$ $\mathrm{km\,s^{-1}}$, and $W = -466$ $\mathrm{km\,s^{-1}}$; U positive towards the GC and V in the direction of Galactic rotation) resulting in a Galactic rest-frame velocity of 563 $\mathrm{km\,s^{-1}}$. This is a lower limit since we assume the proper motion to be zero. Using the Galactic potential of Allen & Santillan (1991) the escape velocity at the position of HE 0437−5439 is 317 $\mathrm{km\,s^{-1}}$ indicating that the star is unbound to the Galaxy.

4. Discussion: Place of birth

Proper motion measurements are needed to reconstruct the full space velocity vector and trace the trajectory of HE 0437−5439 back to its birth place. The Super-COSMOS Sky Survey (Hambly et al. 2001) gives $\mu_\alpha \cos(\delta) = -0.6 \pm 8.8$ $\mathrm{mas\,yr^{-1}}$ and $\mu_\delta = -6.2 \pm 6.9$ $\mathrm{mas\,yr^{-1}}$, i.e. consistent with zero and error limits larger than any plausible value. However, it is possible to compute the flight time for every hypothetical origin in our Galaxy. Each starting point corresponds to a unique set of proper motions. However, evaluation is not straightforward, but has to be computed iteratively. Since common wisdom has it that the most likely origin for hypervelocity stars is the Galactic center, we started by computing

the flight time to the center of the Milky Way.

Calculations were performed with the program ORBIT6 developed by Odenkirchen & Brosche (1992). This numerical code calculates the orbit of a test body in the Galactic potential. The complete set of cylindrical coordinates is integrated and positions and velocities are calculated in equidistant time steps. Trial values for the unknown proper motions were varied until the star passed through the GC with an accuracy of better than 10 pc. Note, that this is a formal result, which assumes a smooth Galactic potential. However, deviations from the computed path caused by close encounters with e.g. other stars in the central region of the Galaxy have only negligible consequences for our considerations. The result was 99 ± 19 Myrs with a predicted proper motion of $\mu_\alpha \cos(\delta) = 0.55$ mas yr^{-1} and $\mu_\delta = 0.09$ mas yr^{-1}.

Such a small proper motion can be measured only by future space missions such as GAIA. The time of flight is much longer than our estimate of the main sequence age of the star (25 Myrs). This prompted us to investigate whether an origin from another location in the Milky Way would yield a sufficiently short time of flight. Thus we repeated this procedure for a grid of hypothetical starting points in the Galactic plane within a radius of 15 kpc from the Galactic center. The results are shown in Fig. 4. Although the flight times from starting points on the HE 0437−5439 side of the disk are smaller, they are always larger than 80 Myrs, i.e. more than three times the apparent age of HE 0437−5439. We performed a simple check in order to investigate how much the results depend on the choice of a specific Galactic potential: We repeated the procedure described above with the numerical values of the Allen & Santillan (1991) potential increased by 50%. This corresponds to an upper limit for the range of escape velocities discussed in literature (cf. Allen & Santillan 1991). The resulting flight times were slightly shorter, but never more than 5 Myrs.

A possible solution of this riddle could be a blue straggler nature of HE 0437−5439. In this scenario a close binary consisting of two stars with about 4 $M_\odot$ was ejected, it came into contact and merged some time after the ejection. Since the main-sequence lifetime of a 4 $M_\odot$ star is 165 Myrs (Schaller et al. 1992), i.e. larger than the flight time, this could resolve the puzzling age discrepancy. In principle it would be possible to eject a close binary after the interaction of a hierarchical triple system with the central black hole of the Milky Way. However, the necessary kick velocity is so high, that probably a lot of fine tuning would be necessary to allow the binary system to survive.

Theoretical calculations testing this scenario are encouraged. We want to point out here that a LMC origin is a feasible alternative.

The projected distance of HE 0437−5439 to the kinematic center of the LMC ($\alpha =$

$5^{\rm h}27\rlap{.}'6$, $\delta = -69°52'$; van der Marel et al. 2002) is 16.3°. This corresponds to 14 kpc at the distance of the LMC (50 kpc; Freedman et al. 2001). Our distance estimate for HE 0437−5439 was 61 ± 12 kpc which puts it 11 ± 12 kpc behind the LMC. We derive a total distance between HE 0437−5439 and the center of LMC of 18^{+9}_{-4} kpc. Thus HE 0437−5439 is much closer to the center of the LMC than to the disk of the Milky Way.

Van der Marel et al. (2002) determined a systematic velocity of the LMC of 262 $\rm km\,s^{-1}$ from a study of a large sample of carbon stars. Thus the relative (radial) velocity of HE 0437−5439 is 461 $\rm km\,s^{-1}$. If HE 0437−5439 was ejected shortly after its birth about 35 Myrs ago from somewhere close to the center of the LMC (see Sect. 3) a tangential velocity of 390 $\rm km\,s^{-1}$ would be necessary to explain its current position 16° away from the center. This corresponds to a proper motion of about 2 $\rm mas\,yr^{-1}$, which could be measured by conventional methods from the ground.

The total ejection velocity would amount to 600 $\rm km\,s^{-1}$ (neglecting the gravitational potential of the LMC) close to the value computed for an ejection from the Milky Way disk. We conclude that the properties of HE 0437−5439 could be well explained by the ejection of a single star from the LMC about 35 Myrs ago. It is not necessary to invoke a blue straggler scenario, which requires a fair amount of fine tuning.

5. Conclusions and outlook

We have shown that HE 0437−5439 is an early B-type hyper-velocity star. Both, chemical abundances and a moderate rotational velocity of HE 0437−5439 provide strong evidence for a main sequence nature of this object. It is considerably more massive than the first object of this class, SDSS J090745.0+024507, which puts tight constraints on the flight time since HE 0437−5439's ejection. Tidal disruption of a close binary by the massive black hole at the GC has been suggested to explain the HVS. However, an origin from the center or the disk of the Milky Way is at variance with its age. Although it is possible to reconcile the age constraint via a blue straggler scenario, we showed that an ejection from the LMC is more plausible.

Our LMC scenario makes two predictions: firstly, we expect that the abundances of HE 0437−5439 should correspond to the LMC metallicity, which is about half solar. Secondly, we predict a proper motion relative to the LMC of 2 $\rm mas\,yr^{-1}$ or higher, depending on the precise location and time of the HE 0437−5439 ejection. Unlike the proper motion predicted for ejection from the Galactic center, the proper motion is large enough to be possibly measurable from the ground.

If an origin in the LMC can be confirmed, this would allow to proof that either the LMC contains a – so far undetected – very massive black hole, or that other mechanisms are capable of producing HVS as well.

We thank the staff of the ESO La Silla and Paranal observatories for their valuable support. We made extensive use of NASAs Astrophysics Data System Abstract Service (ADS) and the SIMBAD database, operated at CDS, Strasbourg, France. R. N. acknowledges support by a PPARC Advanced Fellowship.

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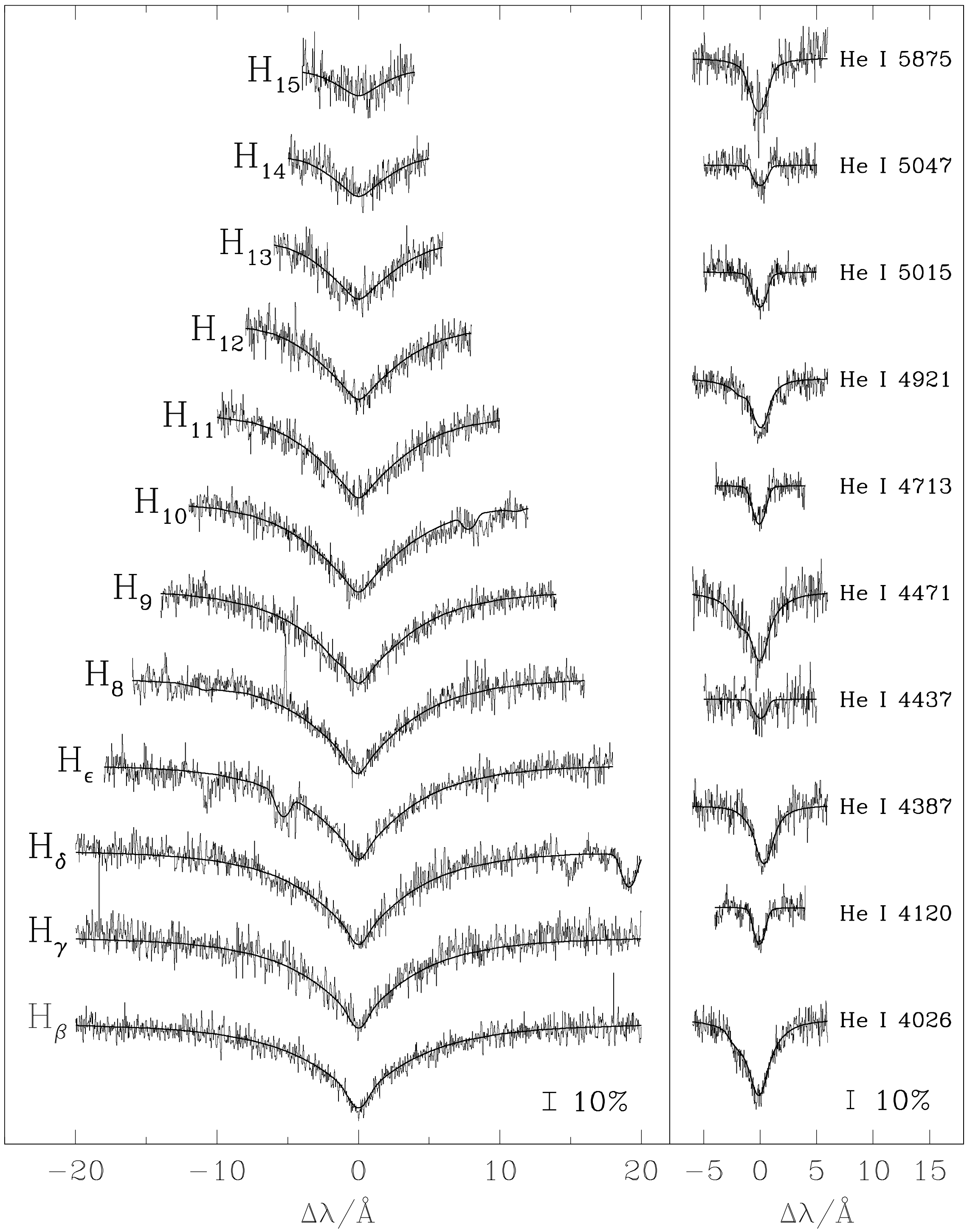

Fig. 1.— LTE fit (thick lines) for HE 0437−5439 for the Co-added UVES spectrum (thin lines).

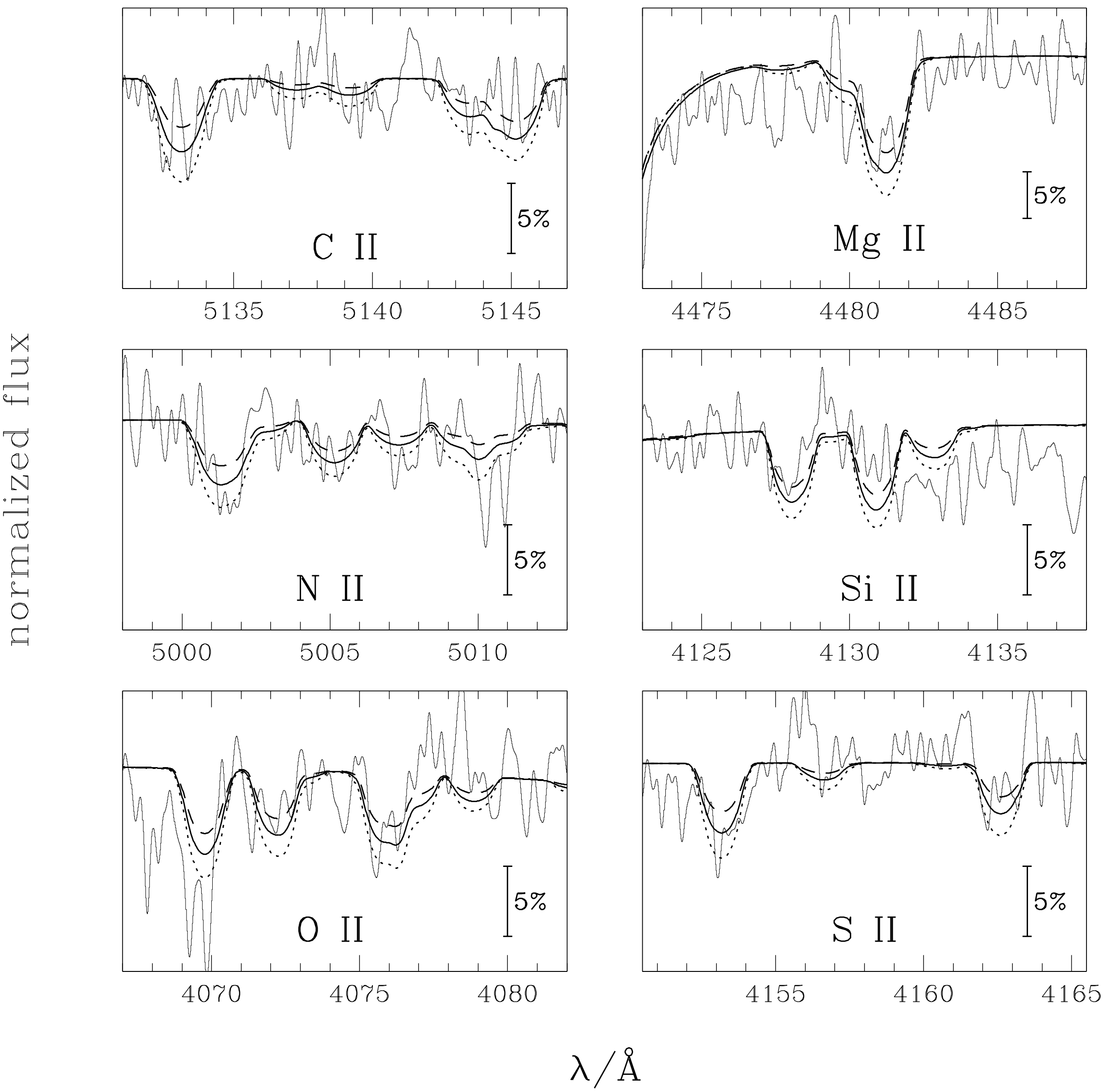

Fig. 2.— Co-added UVES spectrum compared to synthetic spectra with solar metal abundance (solid lines), half the solar metal abundance (dashed lines), and twice the solar metal abundance (dotted lines). Note that for this plot the spectra were binned to 0.4 Å to achieve a S/N of 20.

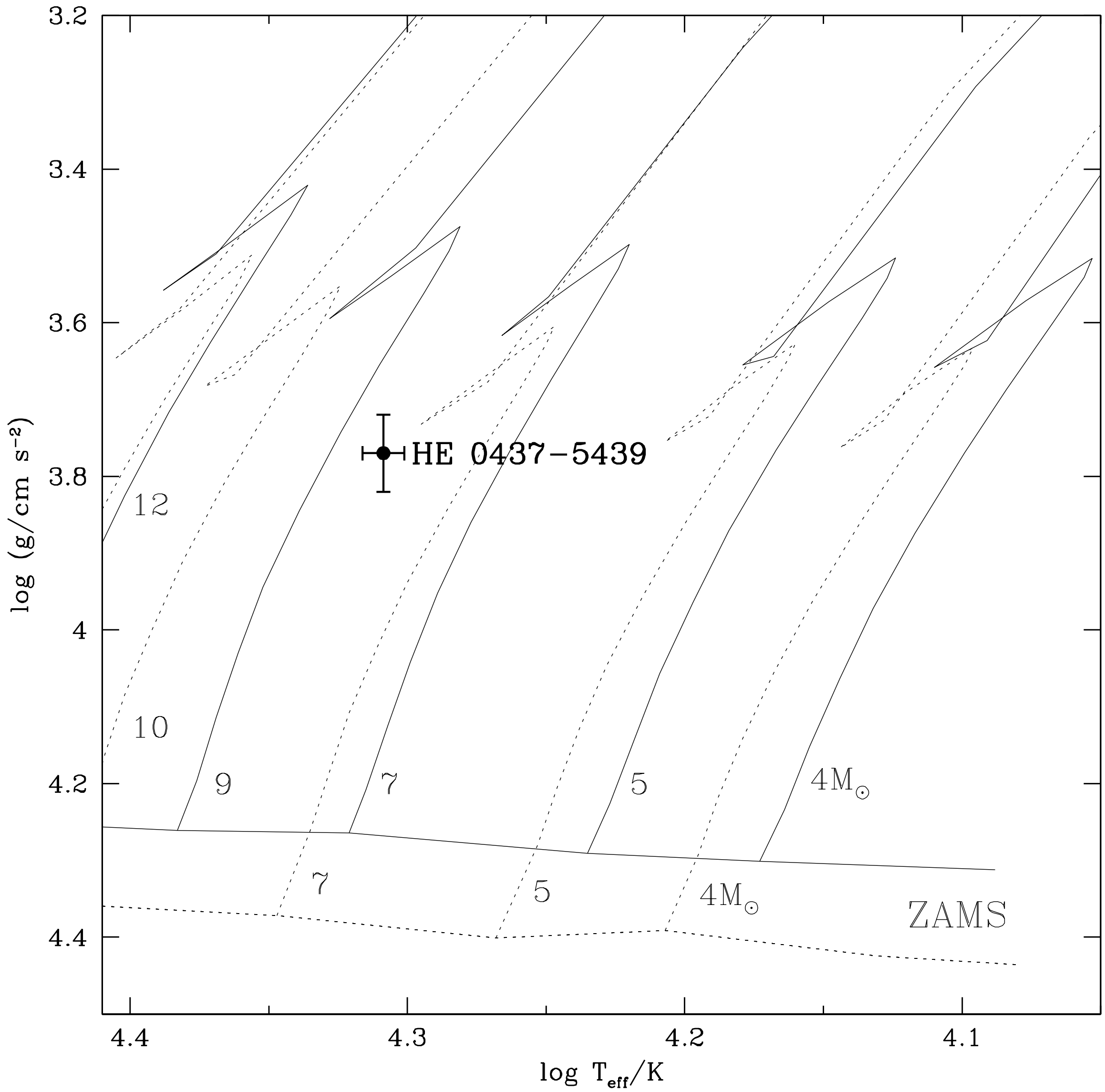

Fig. 3.— Position of HE 0437−5439 in a ($T_{\rm eff}$, log(g)) diagram with evolutionary tracks for solar (Schaller et al. 1992, solid lines) and LMC metallicity (Schaerer et al. 1993, dotted lines) to determining its mass.

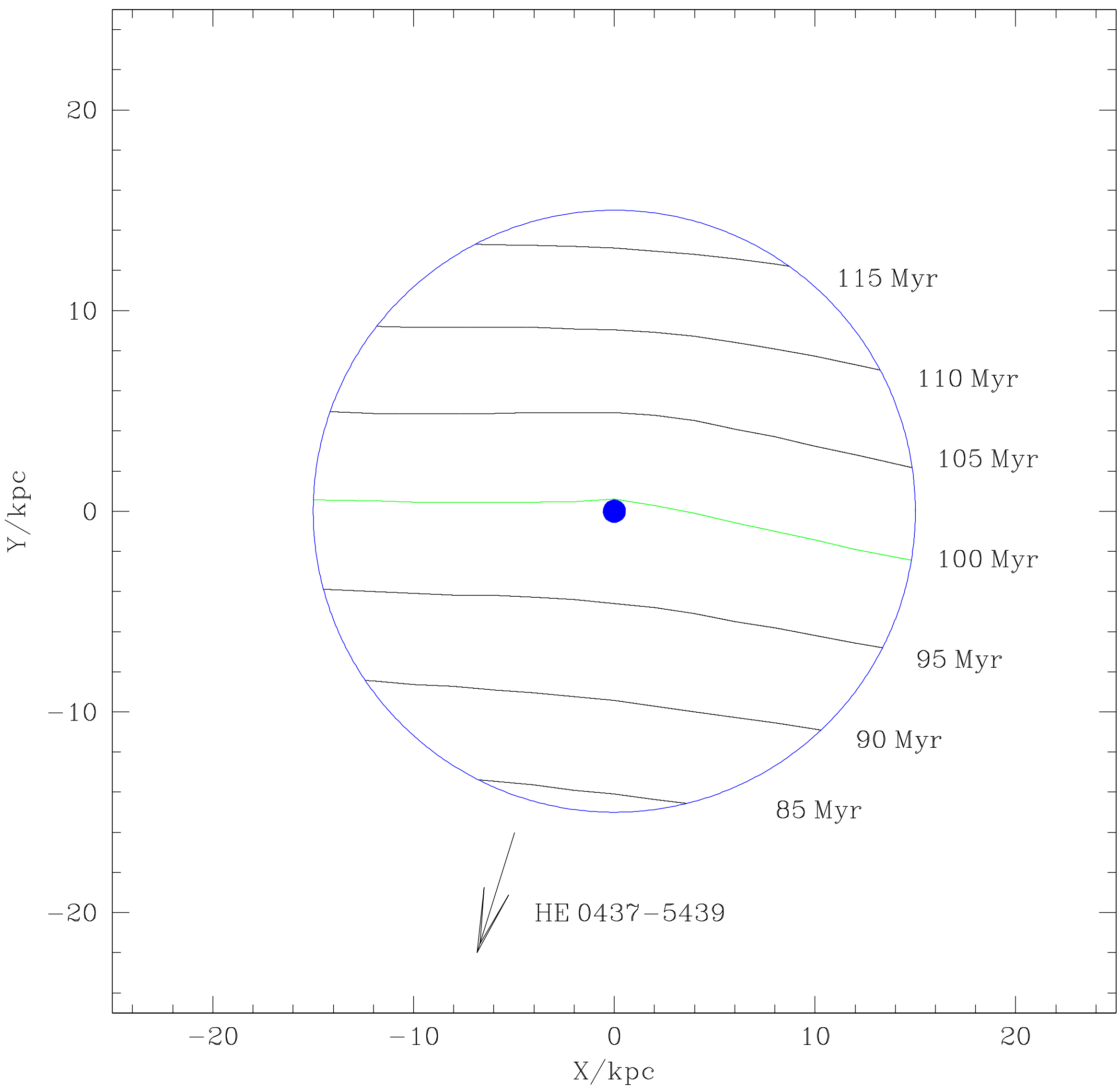

Fig. 4.— Isochrones showing the travel time of HE 0437−5439 from hypothetical starting points in the Milky Way disk to its current position. X and Y are the inplane distances from the Galactic center.